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Ground-based sensing system for weed mapping in cotton☆

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ABSTRACT

A ground-based weed mapping system was developed to measure weed intensity and distribution in a cotton field. The weed mapping system includes WeedSeeker® PhD600 sensor modules to indicate the presence of weeds between rows, a GPS receiver to provide spatial information, and a data acquisition and processing unit to collect and process the weed data and spatial information. The PhD600 sensor module is a commercial product used as a component in this weed mapping system. A prototype of the weed mapping system was field evaluated for 2 years. The system performed well during the field evaluation. Weed intensity in the field was also estimated based on remotely sensed imagery, and these estimates were used to create weed maps. Development of the weed mapping system and its evaluation results are reported in this article.

1. Introduction

1.1. *Literature review*

Technologies of remote sensing and precision agriculture are, in combination, playing an increasingly important role in agricultural production. Because of their potential for high spatial and spectral resolution, satellite and aircraft images can contain detailed site-specific information about conditions in agricultural fields. They can be used for monitoring crop growth, yield potential, soil conditions, weed intensity, etc. (Thomasson et al., 2003; Broner et al., 2002; Varvel et al., 1999). Spectral reflectances from image data have often been used to calculate vegetation indices that have been related to crop growth status. Normalized difference vegetation index (NDVI) is one of the vegetation indices that have been commonly used in remote-sensing applications in agriculture. Goel et al. (2003) used hyperspectral image classification to detect weed infestations and nitrogen status in corn. They found it difficult to distinguish between the effects of weeds and nitrogen treatments. However, when one factor was considered at a time, maps indicating weed infestation or nitrogen treatment could be generated with a satisfactory level of accuracy. Plant et al. (2000) investigated the relationships between remotely sensed reflectance data and cotton growth and yield. The results demonstrated that NDVI integrated over time showed a significant correlation with lint yield. Bajwa and Tian (2001) used an airborne digital color-infrared sensor to acquire remotely sensed images for mapping weed density. In their study multiple regression and artificial neural network approaches were used to build models for weed density prediction that exhibited strong correlations between the predictions and the ground truth. Tian et al. (1999) reported a machine-vision-system-guided precision sprayer. Multiple cameras were used in the sprayer to image crop rows and the images were processed by the com-

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puter to detect weeds and conduct site-specific weed control in real time. Herbicide application amount could be reduced by up to 48% by using that sprayer system. Lamm et al. (2002) developed a real-time robotic weed control system including machine vision, a controlled illumination chamber, and a precision chemical applicator. The system was able to correctly spray 88.8% of weeds in commercial cotton fields at a speed of 0.45 m/s. Downey et al. (2003) reported the use of an automatic weed mapping location and identification system to map nutshedge in a cotton field. The system had an overall accuracy of about 85% and illustrated the potential for significant labor savings over conventional weed mapping methods. Hummel and Stoller (2002) conducted a multi-year study using a herbicide applicator equipped with Pachen's WeedSeeker® PhD600 single-sensor modules. Their results showed that the savings in the amount of glyphosate used to control weeds in corn and soybeans could be up to 80% in a particular year, and that over time the savings could average about 45%. Hanks (1996) used a sprayer equipped with WeedSeeker® optical sensors to apply herbicides in a soybean field. It was found the weeds were killed with only one-half of the herbicide used by the conventional sprayer.

1.2. *Background*

A multi-disciplinary research program on remote-sensing technologies for precision agriculture was conducted at Mississippi State University. One of the studies in this research program was to identify the relationships among airborne multi-spectral imagery and ground truth data of weed intensity and cotton plant canopy coverage in a cotton field in Mississippi's Delta region. In order to obtain the ground truth data of weed distribution, a system which was capable of mapping weed intensity and distribution across a field was needed for conducting the proposed remote-sensing studies.

2. Objectives

Specific objectives of this research project were:

1. To develop a system to collect weed-intensity data with the WeedSeeker® PhD600 sensor modules along with spatial information from a GPS receiver.
2. To compare in a commercial cotton field the weed intensity as estimated with the WeedSeeker® PhD600 with that estimated based on the intensity of electromagnetic radiation between rows, and to identify the relationships among airborne multi-spectral imagery and ground truth data of weed intensity and cotton plant canopy coverage in a cotton field in Mississippi's Delta region.

3. Material and methods

3.1. *System development*

A ground-based weed mapping system was developed to measure weed intensity and distribution in a cotton field. The system includes WeedSeeker® PhD600 sensor modules

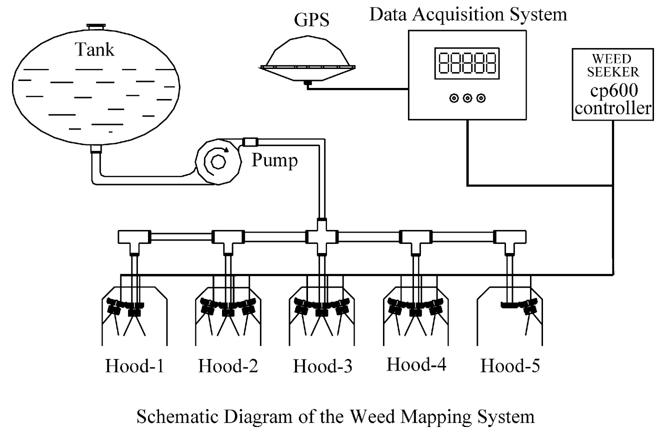

Fig. 1 – Configuration of the weed mapping system.

(Patchen Inc., Ukiah, CA) for weed detection, a GPS receiver for measuring location, and a data acquisition and processing unit to collect and process weed data and spatial information (Fig. 1).

The WeedSeeker® PhD600 sensor module is a commercial product manufactured by NTech Industries Inc. (Ukiah, CA). It is an active optical sensor with its own light source. Its optical and electronic components are housed together in a plastic module (Fig. 2). The sensor is able to detect the presence of a weed by measuring the reflectance of weeds and bare ground in its view. If the sensor identifies a weed, it will output an electronic signal to a solenoid valve that activates a nozzle to spray the weed. PhD600 sensor module was used as a component in the system described in this manuscript to detect weed presence. Because the sensor module used in this system was not capable of distinguishing the weed species, this system was only able to detect and map the vegetation presence between cotton rows. For purposes of this paper, "weed intensity" is used as a shorthand term for "weed intensity as estimated by measured electromagnetic radiation reflected by the vegetation between rows."

A four-row hooded sprayer, which was equipped with the WeedSeeker® selective spray system was employed for weed-intensity data collection. There are five hoods in this four-row sprayer (Fig. 1). Two WeedSeeker® sensor modules were installed under hood 1 at the middle and left side of the

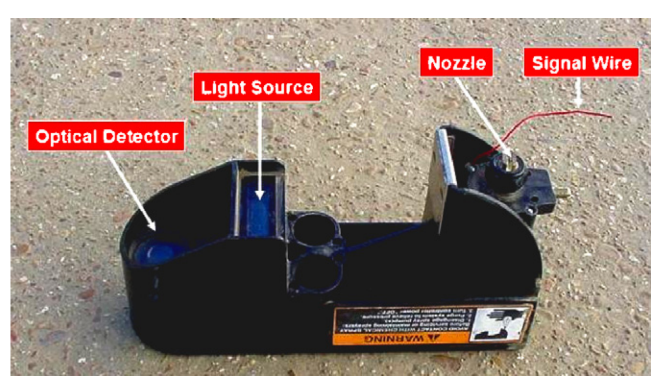

Fig. 2 – WeedSeeker® PhD600 sensor module. A signal wire was added for collecting output data of the sensor.

hood, while only one sensor module was installed in hood 5 on the right side of the hood. Three sensor modules were installed in each of the rest of the hoods (Fig. 1). This was the original setup in the sprayer. In this way, as the sprayer operated in the first round, two sensor modules in hood 1 could "look" and spray the weed on the left and middle of row 1 while the module in hood 5 sprayed the right side of row 5. In another round, two modules in hood 1 would "look" and spray the left and middle of row 5 or the module at hood 5 would spray the right side the row 1 depending upon how the rounds were made during the field operation. It was understood that this setup would decrease the weed detection resolution in hood 1 and 5. However, since the total of the outputs from 12 sensor modules were used to represent the intensity of weed presence at each sampling point and the missing weed under hoods 1 and 5 would be detected in another two rounds and its contribution to the module's output would be added into the two neighbor points, the module setup in this way would not significantly affect the appearance of the weed map which was created using the data collected by the system. An external signal wire was introduced into each sensor module for extracting sensor output (Fig. 2). The signal wire output a higher voltage signal (about 1.15 VDC) if a weed was detected by the sensor, and it output a lower signal (about 0.11 VDC) if no weed was detected. The sum of the outputs of all 12 WeedSeeker® sensors was used to represent the weed intensity at a specific location in the field. Thus, the weed-intensity value varied from about 1.3 to 13.8 V. Signal wires of each sensor were connected to the data acquisition unit with four 6-m long cables. The data acquisition unit and the GPS receiver were installed inside the tractor cab (Fig. 3). GPS antenna was mounted on the top of the tractor cab. The 12 V battery on the tractor was used to provide power to the entire system.

The data acquisition and processing system was based on a single-board-computer (SBC) (SBC-GX1, Arcom, Overland Park, KS) with a 16.5-cm TFT flat panel display (Fig. 3). The SBC-GX1 was a low profile board with a size of 146 mm × 203 mm. It included a 233-MHz processor with standard PC interfaces, and a wide range of expansion options was provided via a CompactFlash socket, PC/104 bus connector and a standard PCI slot. In conjunction with the SBC-GX1, a 16-channel 12-bit

Fig. 3 – Data acquisition system for weed mapping.

analog-to-digital converter (ADC) (AIM104-ADC16/IN8, Arcom) and a 16-bit PCMCIA v2.0 compliant interface card (SDDP-03, Adtron Corp., Phoenix, AZ) were employed in the system for signal processing and data storage. The analog signals from the 12 WeedSeeker® sensors were input to the ADC and then collected and analyzed by the SBC. One serial port of SBC-GX1 was used to record spatial information from a Trimble AgGPS132 differential GPS receiver (Trimble Navigation Limited, Sunnyvale, CA). Dynamic position accuracy of the GPS receiver was 0.1–0.3 m. The GSA and RMC sentences from the receiver were used to provide location, speed, and position dilution of precision (PDOP) data. Location data were differentially corrected with the signal from the nearest U.S. Coast Guard beacon station. The system's data acquisition box read data directly from the DGPS receiver. Weed intensity and spatial information were displayed on a color screen and stored in a flash storage card. And the data could be downloaded from the storage card to a laboratory computer and processed with GIS software such as ArcView® or Arc/Info. Using the collected data, a weed-intensity map could be constructed to show the weed distribution within a field. The GPS antenna was installed on top of the tractor's cab. Distance between the antenna and the sensors was about 2.7 m. This distance was corrected by shifting GPS data in dataset one record backward. GPS data and sensor data were collected simultaneously once per second. One record backward shifting of GPS data was equivalent to about 2.7 m backward movement of the spatial location as the tractor traveled at a speed of 9.7 km/h.

Using a voltage regulator (LM323AK, National Semiconductor) with a heat sink, the 12 V battery on the tractor was converted into a 5 VDC power supply to provide power for the SBC, ADC, and PCMCIA card. The GPS receiver was directly powered by the 12 V battery. All the electronic components were housed in a polycarbonate enclosure (Fig. 3). A 12 VDC fan was installed to reduce heat accumulation inside the enclosure.

A system operation program was developed in C programming language to handle data acquisition and storage. The system was very easy to operate. After the power was turned on, a message was displayed on the screen asking the user to press the START key on the key pad to start data collection. Once the START key was pressed, a text file was created and the data were recorded under the file in the storage card. To stop data collection, user could simply close the data file by pressing the STOP key on the key pad.

3.2. *Field evaluation*

The study site for system evaluations was a 13-ha commercial cotton field located in Stoneville, Mississippi. The field contains mixed soil types (Be-Bosket very fine sandy loam, Dk-Dundee silty clay loam, Dp-Dundee very fine sandy loam; and Sd-Sharkey silty clay loam) and was land-formed to a 0.15-m per 100-m slope (drains from West to East). Tillage of the field was no-till from 2002 to 2003. Cotton was planted in May 2, 2002 and April 29, 2003 for this study.

Field measurements included weed intensity as measured with the weed mapping system, manual measurements of crop canopy coverage, and remotely sensed images from which NDVI was calculated. Dates when field measurements

Table 1 – Relationship among crop canopy coverage, NDVI and weed intensity (C, canopy coverage; W, weed intensity)

Date	Model	R^2	P-value
Weed intensity: 7/10/02; canopy coverage: 7/10/02; NDVI: 7/02/02	C = 72NDVI + 74.6	0.23	0.005
	C = 13.9W − 96.2	0.37	0.0002
	C = 18.8NDVI + 11.9W − 70.9	0.38	0.0009
Weed intensity: 7/10/02; canopy coverage: 7/10/02; NDVI: 7/17/02	C = 98.4NDVI + 59.2	0.48	<0.0001
	C = 13.9W − 96.2	0.37	0.0002
	C = 72.1NDVI + 6.6W − 15.8	0.53	<0.0001
Weed intensity: 6/24/03; canopy coverage: 6/20/03; NDVI: 6/21/03	C = 28.8NDVI + 42.1	0.06	0.1703
	C = 0.47W + 35.5	0.04	0.2689
	C = 23NDVI + 0.2W + 39.7	0.07	0.3670
Weed intensity: 7/14/03; canopy coverage: 7/14/03; NDVI: 7/14/03	C = 70.1NDVI + 50.9	0.39	0.0001
	C = 1.6W + 33.2	0.20	0.0112
	C = 117.4NDVI − 1.8W + 68.6	0.47	0.0002

were made are given in Table 1. In 2002, weed intensity and canopy coverage data were collected only once, but images were collected twice. In 2003, all field measurements were collected twice. The sensitivity level of the WeedSeeker® controller was set to 3 (sensitivity setting from high to low is 1–10) during weed-intensity data collection. The travel speed of the sprayer was about 9.7 km/h. Weed-intensity data from the WeedSeeker® sensors and spatial data from a Trimble AgGPS132 receiver were collected once per second.

Cotton plant growth conditions, including plant height and crop canopy coverage, were measured and recorded at 32 sampling locations within the 13-ha experimental field (Fig. 5). Crop canopy coverage is the percentage of crop vegetation in view (as opposed to bare ground, crop residue, weeds, etc.) when one is looking straight down on the field. To obtain crop canopy coverage, a distance from the leading edge of the plant canopy on one row to the leading edge of the canopy on the next row was measured. Next, crop canopy coverage was calculated by dividing the difference between row spacing and the measured distance by the row spacing (0.97 m).

Four-band images of the study site were acquired by Geodata Inc. with their GeoVantage® imaging system. Flight

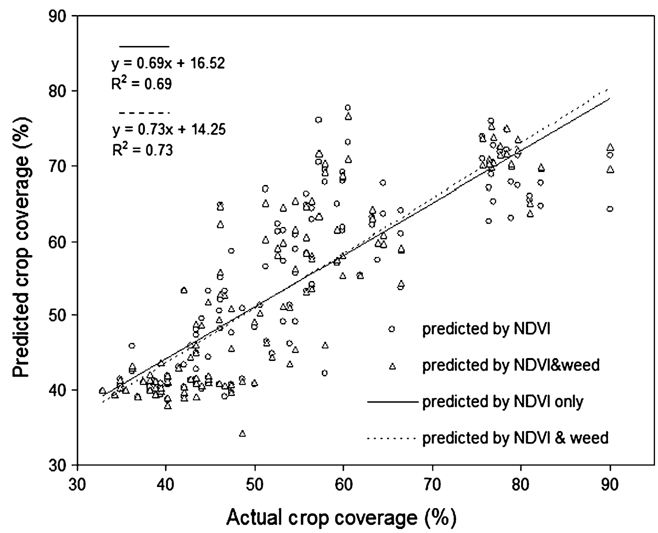

Fig. 4 – Predicted crop canopy coverage vs. actual crop canopy coverage.

Table 2 – Illustration of data collected using the weed mapping system

Latitude	Longitude	Speed (mph)	PDOP	Row 1 (v)	Row 2 (v)	Row 3 (v)	Row 4 (v)	Total (v)
33.43597	−90.890503	7.28	1.4	2.92	1.66	2.03	1.53	8.14
33.43597	−90.890465	7.45	1.4	2.89	1.27	1.67	1.80	7.64
33.43597	−90.890427	7.31	1.4	2.91	1.53	1.88	2.12	8.44
33.43597	−90.890388	7.33	1.4	2.95	1.23	2.15	2.05	8.38
33.43597	−90.89035	7.45	1.4	2.89	1.20	1.63	1.91	7.63
33.43597	−90.890327	7.35	1.4	2.87	1.63	1.56	2.10	8.15
33.43597	−90.890289	7.3	1.4	2.87	1.26	1.36	1.86	7.34
33.43597	−90.890251	7.33	1.4	2.69	1.34	1.27	1.20	6.51
33.43597	−90.890213	7.49	1.4	2.42	1.17	1.52	0.89	5.99
33.43597	−90.890175	7.34	1.4	2.38	1.16	1.75	0.76	6.05
33.43597	−90.890144	7.38	1.4	2.25	1.05	1.46	0.93	5.69
33.43597	−90.890106	7.46	1.4	1.73	0.70	1.11	0.52	4.06
33.43597	−90.890068	7.28	1.4	1.90	0.75	1.00	1.14	4.79
33.43597	−90.89003	7.3	1.4	1.70	1.14	1.67	0.93	5.44
33.43597	−90.890007	7.34	1.4	1.39	1.34	2.17	1.36	6.25
33.43597	−90.889969	7.18	1.4	1.39	1.06	1.21	0.77	4.44
33.43597	−90.889931	7.12	1.4	1.41	0.92	1.05	1.03	4.41

altitude was approximately 1300 m. A mosaic image was created from individual scenes with tools available in Erdas Imagine® software. The resulting image resolution was approximately 0.5 m. The blue band of the images was centered at 450 nm, the green at 550 nm, the red at 650 nm, and the near-infrared (NIR) at 850 nm. NDVI was calculated on a pixel-by-pixel basis by dividing the difference between the NIR and red digital numbers by the sum of NIR and red digital numbers; i.e., NDVI = (NIR − red)/(NIR + red).

The weed map data consisted of a series of locations (latitude and longitude) with a weed-intensity value. Image digital numbers were extracted for each weed-intensity location as follows. A square buffer area with sides of 1 m was constructed around each weed-intensity location. An average, weighted by the area of the portion of each pixel in the buffer area, was calculated with software written in the C++ programming language (see equation below).

$$\text{Wt\_average} = \frac{\sum \text{pix\_value} \times \text{pixel\_area\_in\_buffer}}{\text{buffer\_area}}$$

where Wt_average: average of pixel values weighted for the actual area of each pixel in the buffer area; Pix_value: digital number of pixel; Pixel_area_in_buffer: actual area of the pixel that lies within the buffer area; Buffer_area: area of the buffer around sample location.

Values of the Wt_average for each of the four image bands were combined with the weed-intensity data. Using the same method as described above, both image digital numbers and weed intensities were extracted around each canopy coverage sampling point with a 10 m × 10 m square buffer.

After extracting image data, each record in the dataset included latitude, longitude, speed, weed intensity, and image

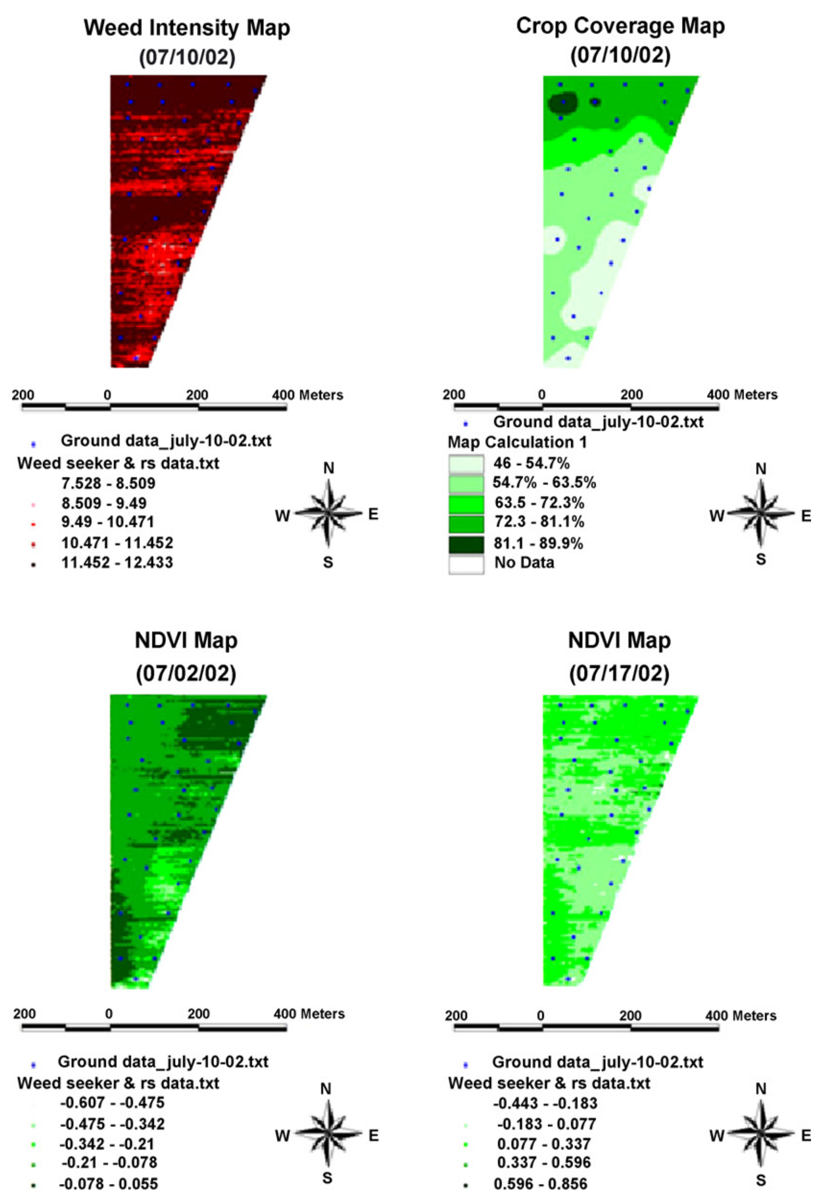

Fig. 5 – Comparison of weed-intensity map on 07/10/02 with crop canopy coverage map on 07/10/02 and NDVI maps on 07/02/02 and 07/17/02. The blue dots shown on the maps were the canopy coverage sampling points.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

values for bands 1–4. Then, NDVI was calculated at each weed-intensity location by dividing the difference between the NIR and red weighted-average digital numbers by the sum of NIR and red weighted-average digital numbers; i.e., NDVI = (NIR − red)/(NIR + red). For the purpose of having visual comparisons, weed-intensity maps, NDVI maps, and crop canopy coverage maps were created with ArcView®.

Data including crop coverage, weed intensity, and NDVI were analyzed with the REG procedure in SAS®. Parameter coefficients and coefficients of determination (R^2) were obtained in the regression analyses and used to compare linear relationships between crop canopy coverage and NDVI, crop canopy coverage and weed intensity, and crop canopy coverage and NDVI plus weed intensity.

4. Results and discussion

No hardware and software failures were observed during field evaluations. The system performed well in collecting weed data along with spatial information for creating weed maps of the field. In each evaluation, approximately 10,000 readings were taken from each WeedSeeker® sensor and the GPS receiver. A small portion of the data file was illustrated in Table 2. The data file includes latitude, longitude, speed, PDOP, outputs from each WeedSeeker® sensor, and the sum of the

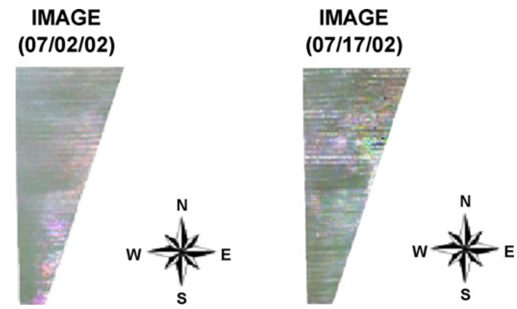

Fig. 6 – Color-infrared images taken on 07/02/02 and 07/17/02.

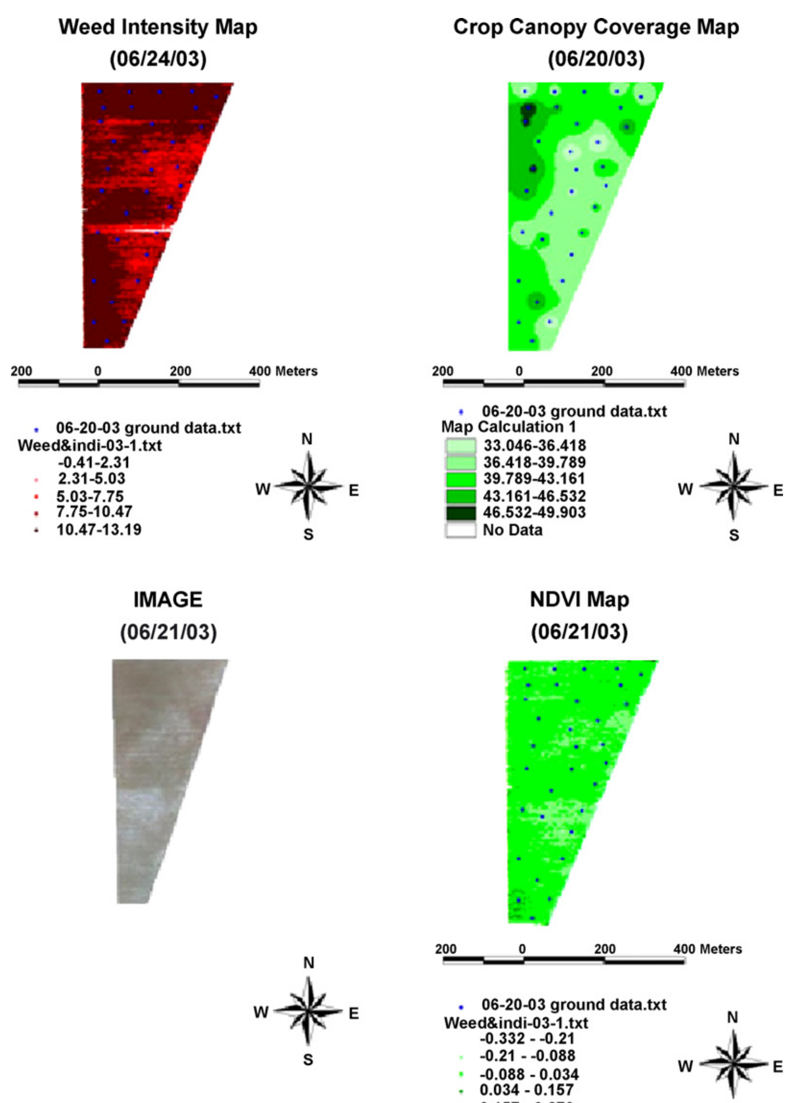

Fig. 7 – Showing weed-intensity map, crop canopy coverage map, the color-infrared image, and NDVI map at late June of 2003.

sensor output. The output value of the sensor was proportional to the weed intensity on the ground. As ground truth of weed distribution, the data collected by the system were effective for use in remote-sensing research in the study site.

Results of the analyses to determine relationships between crop canopy coverage and NDVI, crop canopy coverage and weed intensity, and crop canopy coverage and NDVI plus weed intensity were given in Table 1. For all comparisons except June 2003, crop canopy coverage was significantly correlated with NDVI plus weed intensity. However, none of relationships were particularly strong ($0.20 \leq R^2 \leq 0.53$). The crop canopy coverage was most closely correlated with NDVI and with NDVI plus weed intensity in July 2002. The R^2 values were 0.48 and 0.53, respectively. In June 2003, the crop canopy coverage had no significant relationship with weed intensity and NDVI. This was likely due to the early growth stage of the cotton plants, which would tend to cause NDVI to be very low and thus result in very noisy data. In general, the poor R^2 values for the regression models could mainly attributed to the variation of soil background and earlier stage of plant growth. Both NDVI and the WeedSeeker® data could be affected by moisture, color, and type of the soil. The evaluation-field was a non-irrigated field with various soil types and the soil was not uniformly dry during acquisition of the images. Non-uniformity of the soil background might introduce significant noise to the data set. All field-evaluations were conducted before the plant canopy was closed. The models at later growth stage had a higher correlation between crop canopy coverage and NDVI than that at earlier growth stage (Table 1). This result indicated that more canopy coverage could reduce the influence of soil background variation on NDVI and WeedSeeker® data.

It was found that models that have NDVI and weed intensity as independent variables also performed better at estimating crop canopy coverage than did the models that have only NDVI as an independent variable. This suggests that weed-intensity information was a useful additional predictive

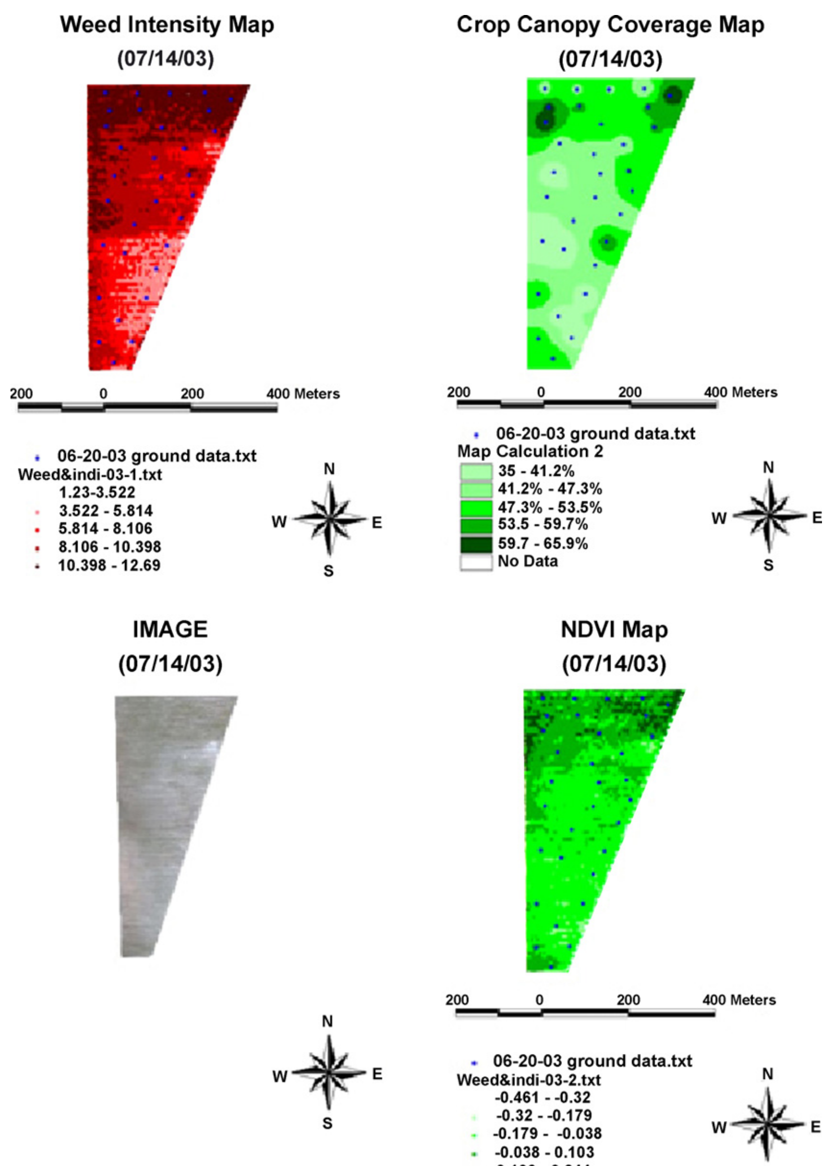

Fig. 8 – Showing weed-intensity map, crop canopy coverage map, the color-infrared image, and NDVI map on July 14, 2003.

variable when NDVI was being used to predict plant growth and development. Fig. 4 is a plot of actual crop canopy coverage versus predicted crop canopy coverage. The predicted crop canopy coverage determined with the model including both NDVI and weed intensity as independent variables had a stronger correlation with the actual crop canopy coverage ($R^2 = 0.73$) than that predicted with the model including only NDVI as an independent variable ($R^2 = 0.69$).

Fig. 5 includes weed intensity and crop canopy coverage maps created with data collected on 07/10/02. The NDVI maps resulting from both July 2002 images are shown in Fig. 5 as well. Fig. 6 includes color-infrared images corresponding to the NDVI maps in Fig. 5. It could be observed that a similar pattern exists in the maps and images of Figs. 5 and 6. Weed intensity at the top of the weed-intensity map was heavier than in the rest of the field. Crop canopy coverage and NDVI also tended to be greater in this portion of the field. However, in the middle of the field from west to the east, a strip on the weed-intensity map exhibited high weed intensity, while in the same part of the field NDVI was high but crop canopy coverage was not.

Figs. 7 and 8 include maps created with data collected in late June and on 14 July 2003, respectively. It was observed that the crop canopy coverage map in both figures did not match the NDVI map well in terms of relative magnitude. But if the pattern of the crop canopy coverage map was visually combined with the pattern of the weed-intensity map, a pattern very similar to that of the NDVI map would appear. This result makes sense because both crop coverage and weed intensity apparently relate to NDVI.

5. Conclusions

A weed mapping system was developed and field evaluated. The system included WeedSeeker® PhD600 sensor modules for weed detection, a GPS receiver for measuring location, and a data acquisition and processing unit to collect and process weed data and spatial information. The weed mapping system was evaluated in a commercial cotton field over 2 years. Results of the field tests were that the system was reliable – no operational problems occurred – and easy to use. Weed-intensity data that were collected with the system were analyzed along with remote-sensing and crop growth data. It was observed that both weeds between rows and crop canopy had significant relationships with remotely sensed images. Weed stress should be taken into consideration when remotely sensed reflectance data from a field are used to predict crop growth and development. This weed mapping system had provided useful tool for the remote-sensing research project in collecting ground truth data, and it also has a potential to be used for precision agriculture.

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